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## Crystallographic Analysis of Orientational Variants in $\text{PbZr}_{0.52}\text{Ti}_{0.48}\text{O}_3$ Ferroelectric Perovskite

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The ferroelectric perovskite  $\text{PbZr}_{1-x}\text{Ti}_x\text{O}_3$  has been extensively studied due to its unique physical properties. It exhibits an unusual morphotropic phase boundary (MPB) which divides the regions with rhombohedral and tetragonal symmetry in its phase diagram. Upon cooling,  $\text{PbZr}_{0.52}\text{Ti}_{0.48}\text{O}_3$  (PZT) undergoes a ferroelectric transition from cubic (C) to tetragonal (T) at about 600K. Recently, a tetragonal to monoclinic (M) phase transition was discovered at about 300K, revealing new characteristics of the MPB [1]. The relationship between T and M follows:  $a_m \sim a_T + b_T$ ,  $b_m \sim -a_T + b_T$ ,  $c_m \sim c_T$ . In this short presentation, we report twin structures formed during the transition of C to T and T to M in PZT at room temperature using transmission electron microscopy (TEM).

The transition from C to T in PZT results in the crystal symmetric change from  $\text{Pm}\bar{3}\text{m}$  to  $\text{P}4\text{mm}$  with the loss of point symmetry elements. The point group of the C phase is  $G = \text{m}\bar{3}\text{m}$ , while that of the T phase is  $H = 4\text{mm}$ , where H of order q ( $q=8$ ) is a subgroup of G, of order p ( $p=48$ ). So six orientation variants are expected in the T phase. Table 1 lists all variants with their corresponding symmetry operations. The M phase has 4 orientation variants with respect to the T phase since its point group is  $H = \text{Cm}$  of order  $r=2$ . Because the M phase will inherit the variants from the T phase, it has totally 24 variants with respect to the C phase.

Fig.1(a) shows a typical morphology of the T phase. Three variants  $\text{TV}_1$ ,  $\text{TV}_2$  and  $\text{TV}_6$  are present. Considering  $\text{TV}_1$  as the matrix, the  $\text{TV}_2$  is the  $(\bar{1}01)$  reflection twin, while the  $\text{TV}_6$  is the  $(\bar{1}01)(101)$  secondary twin. Fig.1(b) and (c) are, respectively, the high resolution image (HREM) and its corresponding electron diffraction pattern (EDP) viewed along  $[010]_{\text{TV}_1}/[001]_{\text{TV}_3}$  direction of the  $\text{TV}_1$  and  $\text{TV}_3$  variants. The boundary  $(0\bar{1}1)$  plane is inclined  $\sim 46^\circ$ . The displacement of Zr/Ti along c-axis can be seen in the insert II. The simulation by multislice method in insert II' shows that the displacement of Zr/Ti along c-axis is bigger than that measured by x-ray diffraction [1]. Furthermore, TEM experiments showed that the displacement of Zr/Ti varies from grain to grain. Thus the smaller displacement value measured by x-ray diffraction is likely due to the nature of the volume averaged x-ray probe.

The room temperature monoclinic phase is shown in fig.2. The HREM (fig.2a) is rotated  $45^\circ$  with respect to its EDP (fig.2b). Two variants  $\text{MV}_1$  and  $\text{MV}_3$  are present in fig.2 with  $(\bar{1}\bar{1}1)$  reflection twin relationship. The EDP of the M phase is similar to that of the T phase but the spots of the  $h\bar{h}0$  row in the former split while those of the corresponding row in the latter do not. Similar to that of the T phase, the displacement of the Zr/Ti along the a and c axes can also be observed (fig.2a). The displacement of Zr/Ti along the a and c axes were determined by comparison with the image simulation. They were found to be 0.029 and 0.037 nm, respectively, which are slightly larger than those measured by x-ray diffraction.

### References:

- [1] B. Noheda et al, Phys. Rev. B, 61 (2001) 8687.
- [2] Work supported by US DOE under contract No. DE-AC02-98CH10886.

TABLE 1 Orientation variants and the essential operations in cosets of the T phase.

Variant	Coset	Essential operations in coset
TV <sub>1</sub> [001]	H=P4mm	1, 2[001], 4 <sup>+</sup> [001], 4 <sup>-</sup> [001], m[010], m[110], m[1 $\bar{1}$ 0], m[100]
TV <sub>2</sub> [100]	m[ $\bar{1}$ 01]	m[ $\bar{1}$ 01], 4 <sup>-</sup> [010], 3 <sup>+</sup> [1 $\bar{1}$ 1], 3 <sup>+</sup> [ $\bar{1}$ 11], 2[101], 3 <sup>+</sup> [ $\bar{1}$ 11], 3 <sup>+</sup> [111], 4 <sup>+</sup> [010]
TV <sub>3</sub> [010]	m[0 $\bar{1}$ 1]	m[0 $\bar{1}$ 1], 4 <sup>+</sup> [100], 3 <sup>-</sup> [ $\bar{1}$ 11], 3 <sup>-</sup> [1 $\bar{1}$ 1], 4 <sup>-</sup> [100], 3 <sup>-</sup> [1 $\bar{1}$ 1], 3 <sup>-</sup> [111], 2[011]
TV <sub>4</sub> [ $\bar{1}$ 00]	m[101]	m[101], 4 <sup>+</sup> [010], 3 <sup>+</sup> [1 $\bar{1}$ 1], 3 <sup>+</sup> [111], 2[ $\bar{1}$ 01], 3 <sup>+</sup> [1 $\bar{1}$ 1], 3 <sup>+</sup> [ $\bar{1}$ 11], 4 <sup>-</sup> [010]
TV <sub>5</sub> [0 $\bar{1}$ 0]	m[011]	m[011], 4 <sup>-</sup> [100], 3 <sup>-</sup> [111], 3 <sup>-</sup> [1 $\bar{1}$ 1], 4 <sup>+</sup> [100], 3 <sup>-</sup> [1 $\bar{1}$ 1], 3 <sup>-</sup> [ $\bar{1}$ 11], 2[0 $\bar{1}$ 1]
TV <sub>6</sub> [00 $\bar{1}$ ]	m[001]	m[001], 1, 4 <sup>-</sup> [001], 4 <sup>+</sup> [001], 2[100], 2[ $\bar{1}$ 10], 2[110], 2[010]

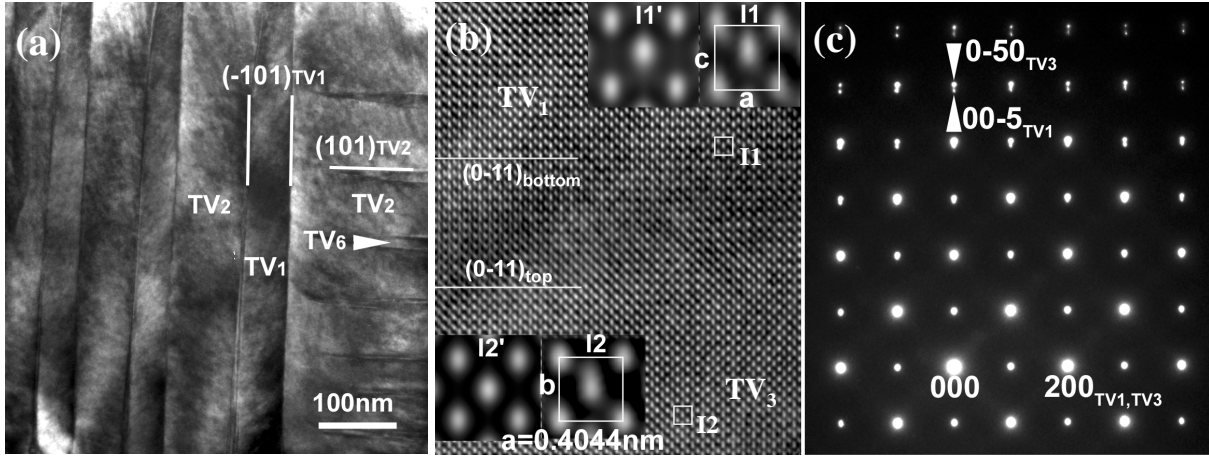


FIG.1. (a) A typical morphology of the tetragonal phase, the twins are clearly seen. The  $(\bar{1}01)_{TV1}$  boundary between TV<sub>1</sub> and TV<sub>2</sub>, and the  $(101)_{TV2}$  boundary between TV<sub>2</sub> and TV<sub>6</sub> are both viewed edge on. (b,c) High resolution image (b) and its corresponding electron diffraction pattern (c) viewed along  $[010]_{TV1}/[001]_{TV3}$  direction. The twin is the  $(0\bar{1}1)$  reflection twin. The twin plane  $(0\bar{1}1)$  is inclined  $\sim 46^\circ$ . The inserts are magnified images of the boxed areas I1 and I2, while I1' and I2' are the simulation.

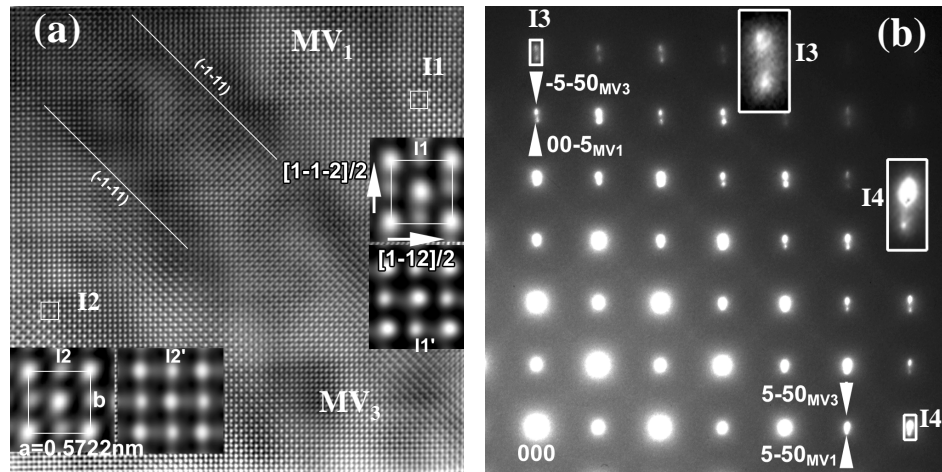


FIG.2. A high resolution image (a) and its corresponding diffraction pattern (b) of the monoclinic phase viewed along  $[110]_{MV1}/[001]_{MV3}$  direction. Note, the high resolution image rotates  $45^\circ$  with respect to the diffraction pattern. The MV<sub>3</sub> is the  $(\bar{1}\bar{1}1)$  reflection twin. The twin plane  $(\bar{1}\bar{1}1)$  is inclined  $\sim 46^\circ$ . The inserts are magnified pictures from the boxed areas, while I1' and I2' are the simulation. The diffraction pattern in fig.2b is similar to that in fig.1c except splitting of the spots in  $h\bar{h}0$  row.